Wall Panels using CFRP Grid

Structurally Composite, Thermally Efficient Precast Concrete

Precast concrete insulated wall panels have been used for decades as both loadbearing structural systems and as building envelopes. Panels are constructed with an inner and an outer wythe of concrete separated by a core of rigid foam insulation. Thermal efficiency is provided by the insulation and isolated thermal mass, while structural efficiency can be maintained by connecting the layers of concrete through the insulating core. Panels can be designed to behave in either a fully-composite, non-composite, or partially-composite manner, depending on the type and number of connections provided between the concrete wythes. Thinner and lighter panels can be produced as higher degrees of composite action are achieved.

The shear connections that join the inner and outer wythes through the foam core play a big role in both the thermal and structural behavior of a panel. Traditionally, connections that provide good structural performance have reduced thermal performance. For example, connecting the inner wythe to the outer wythe with discrete zones of solid concrete can provide a high degree of structural composite action, but also creates a significant thermal break in the insulation, allowing heat to move from wythe to wythe. Similarly, connecting the inner and outer wythes of concrete with a steel truss provides a high degree of composite action, but compromises thermal efficiency by creating thermal breaks in the insulation.

Carbon-fiber reinforced polymer (CFRP) grids are being used in a new generation of composite wall panels to achieve structural composite action while maintaining thermal efficiency. Full composite behavior can be achieved by connecting the concrete wythes with strips of CFRP grid oriented at 45-degrees, as shown in Figure 1. Continuous or semi-continuous strips of CFRP grid are embedded in the concrete at the foam-concrete interface on either side of the insulating core. The grid passes through slits in the foam core, but does not create a thermal break due to the inherent lack of thermal conductivity in CFRP composites. In addition to offering solid structural and thermal performance, CFRP grid provides the additional benefit of high corrosion resistance.

Fabrication

Composite precast concrete panels are fabricated in a long-line precast concrete production facility. In some cases, panels are prestressed, but can also be designed using only conventional mild steel reinforcement. Panels are produced flat with the outer finished surface facing down in the form. Reinforcement for the outer concrete wythe is placed in the empty form, including lon-

gitudinal prestressing if required. Special finishes, such as thin-brick inlay, can also be placed in the bottom of the empty form, prior to casting the outer wythe concrete. With the outer wythe reinforcement and finish materials placed in the form, the concrete for the outer wythe is cast and leveled to the correct thickness. Rigid insulation and CFRP grids are then pressed into the wet outer wythe concrete. The CFRP grids are generally pre-installed in slits in the rigid insulation, protruding at least one half inch from the insulation on each side. With the insulation and CFRP grid in place, the inner wythe reinforcement is added above the rigid foam insulation. As with the outer wythe, the inner wythe may be reinforced with mild steel, welded-wire reinforcement, prestressing strands, or a combination of materials. Embedments for structural connections, utilities, and handling are often required on the inner wythe and may also be placed at this stage. Care must be taken during production to avoid damaging the CFRP grid protruding from the foam core.
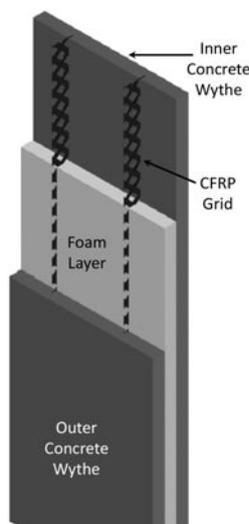

Fig. 1: Cut-Away Views of Composite Panels using a CFRP Grid Wythe Connection. Schematic (left), Photograph (right)

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Fig. 2: Casting the Inner Wythe Concrete in a Sandwich Wall Panel using CFRP Wythe Connections

With inner wythe reinforcement in place, the inner wythe concrete is cast and leveled to the correct depth, as shown in Figure 2. The concrete surface may be finished as required, depending on the final application.

Research and Development

The CFRP shear grid wythe connection has undergone extensive testing, much of it at North Carolina State University in Raleigh, NC. The CFRP grid connections create composite action through a truss mechanism that develops in combination with the rigid foam insulation. Thus, examining all components of the sandwich wall panel is important to understanding panel behavior and optimizing panel design. Tests conducted on the CFRP composite sandwich wall panel system include: material tests on the CFRP grid and insulation; load tests on small sections of panel intended to directly measure shear transfer; tests on full-height panels subjected to combined axial and lateral loads; tests on long-span panels subjected to lateral loads; and tests on a building envelope system subjected to reverse-cyclic uniform pressure loading.

Push-Tests

When designing a composite sandwich wall panel, it is necessary for the designer to know the in-plane shear capacity and stiffness of the wythe connection. These parameters are critical factors in determining how much CFRP grid is required to provide the desired degree of composite action in a particular panel. The in-plane shear capacity of the CFRP grid connection has been evaluated using a special multi-wythe push-out specimen. The push-out specimens measured approximately 2 meters tall by up to 2 meters wide. They were specially configured for testing with 3 layers of concrete and 2 cores of rigid insulation, as shown in Figure 3. The specimens were configured to directly load the concrete-foam interface in shear, activating the CFRP grid shear transfer mechanism.

The testing configuration shown in the figure was selected to minimize the effect of eccentricity of the applied shear force. Each specimen was supported vertically at the bottom edge of the outer two concrete wythes, creating a gap between the laboratory floor and the bottom surface of the center concrete wythe. Load was applied evenly to the top surface of the inner concrete wythe by hydraulic jacks and steel tubes. As load was applied, the center wythe was forced downward with respect to the outer wythes. A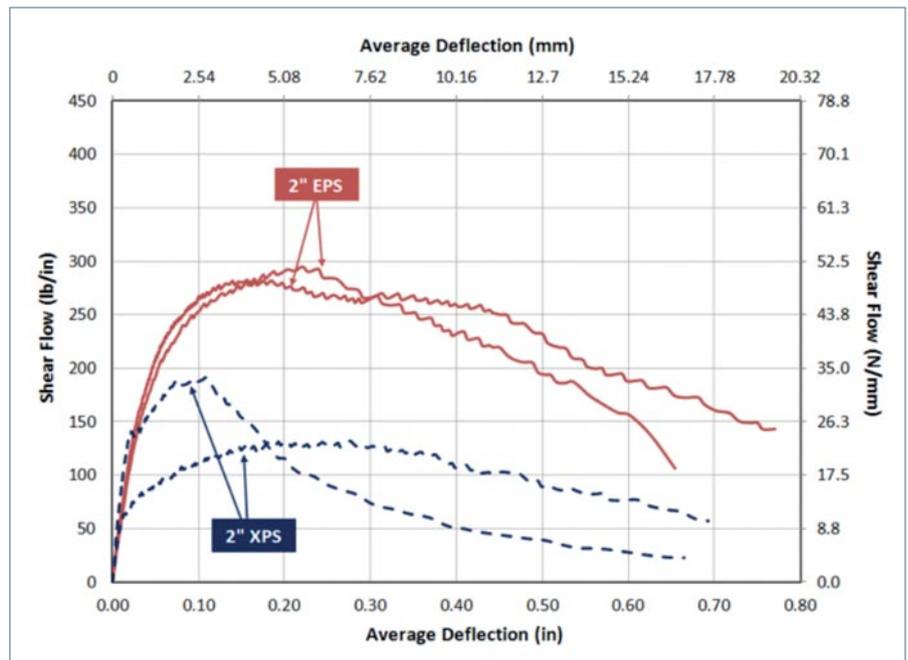 load cell was used to measure the applied load, and linear potentiometers were used to measure the relative vertical and horizontal displacements between the three concrete wythes at the top, bottom, and mid-height of each panel.

Measured load-deflection relationships for selected typical panels are shown in Figure 4. Test results indicate that several parameters have a pronounced effect on the shear capacity of the CFRP grid connectors including insulation type, insulation thickness, and insulation roughness. Test results indicate that CFRP grid connectors used with expanded polystyrene (EPS) foam insulation provide a greater shear resistance as compared to the same connectors used with extruded polystyrene foam (XPS). The EPS insulation appeared to develop a better bond with the concrete, improving the effectiveness of the truss mechanism developed by the CFRP shear grid connections.
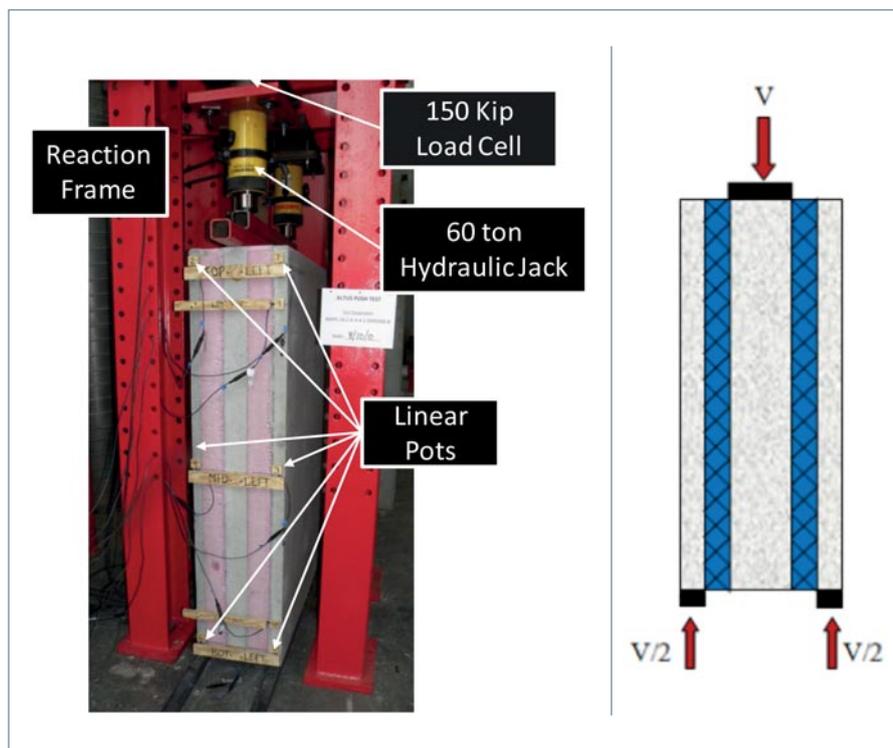
The typical failure mode observed in the push tests consisted of shear cracking developing in the EPS insulation and shear slipping at the bond interface of the XPS, as shown in Figure 5. It was observed that all tested panels exhibited rupturing of the grid tension cords and buckling of the compression cords, as shown in Figure 6. The photographs in Figure 6 were taken after testing and removing the insulation to the depth of the grid.

Tests of Long-Span Panels in Flexure

In order to augment the results from the small-scale push specimens, six full-scale precast, prestressed insulated wall panels were designed and tested to evaluate their flexural response under combined vertical and lateral loads, or under lateral loads only. The study included two sizes of panels, fabricated with two different types of foam, and different quantities of shear reinforcing grid, as shown in Table 1. Four panels were 6.1 m (20 ft) tall by 3.7 m (12 ft) wide, as shown in Figure 7. This group of
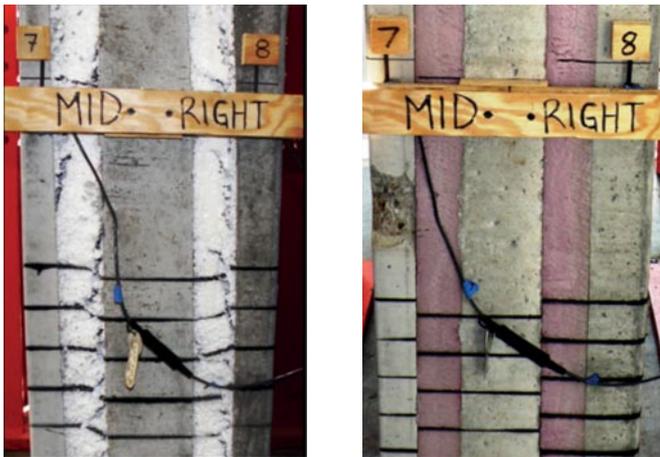

Fig. 4: Typical Load Deflection Behavior for Panels with 2" Foam Insulation

Fig. 3: Push Test Configuration; Photograph (left), Loading Schematic (right)

Fig. 5: Cracking of EPS and Slipping of XPS at Failure

Fig. 6: Typical Observed Failure of the CFRP Grids

panels was tested under combined axial and lateral loads. The remaining two panels were 12.8 m (42 ft) tall and 1.8 m (6 ft) wide, as shown in Figure 2. These panels were tested under lateral loads only to isolate the flexural behavior of the inter-wythe CFRP shear reinforcement. All six tested panels were 203 mm (8 in.) thick, and consisted of three layers through their thickness. The layers were arranged in what is known as a 2-4-2 configuration. A 51 mm (2 in.) thick layer of concrete formed the outer wythe of the panels, a 102 mm (4 in.) layer of foam formed the core, and another 51 mm (2 in.) layer of concrete formed the inner wythe. To resist the axial loads typically imposed at these corbels, the inner wythe of all panels also included two internal pilasters 51 mm (2 in.) thick by 610 mm (24 in.) wide along the full height of each panel at the quarter and three-quarter widths, as shown in Figure 8. Two corbels were included on the inner wythe of all 6.1 m (20 ft) specimens. Axial load was not applied to the 12.8 m (42 ft) specimens, and thus, corbels were not included.

Panels having an expanded polystyrene (EPS) foam core and panels having an extruded polystyrene (XPS) foam core were evaluated in both sizes. In addition, two different shear grid reinforcement

Fig. 7: Cross-section of 6.1 m (20-ft) tall Panels Showing Two Internal Pilasters
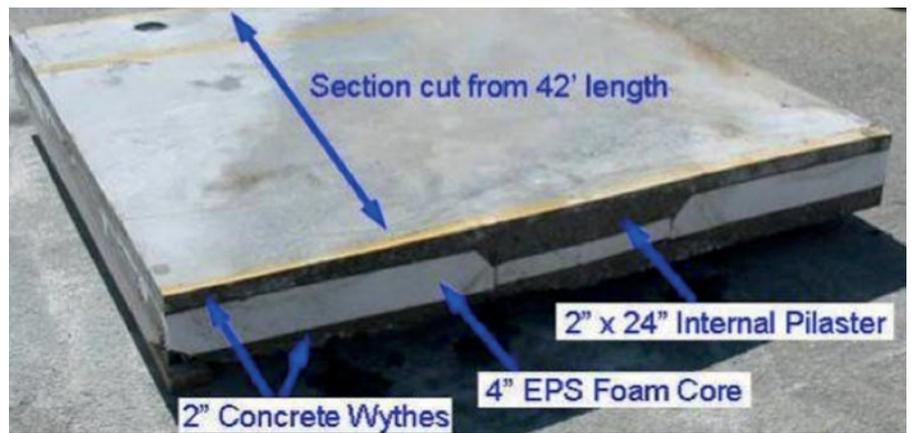
Fig. 8: Pilaster Internal to the 12.8 m (42 ft) Panels

ratios were examined in each group of similarly sized panels. In all panels, CFRP shear grid was placed through the foam core, to bridge the two concrete wythes, transferring shear stresses across the foam and developing a composite action. Mild and prestressed steel reinforcement was provided in both concrete wythes of both types of panel. Each wythe was reinforced in the plane of the wythe and also prestressed in the longitudinal direction.

Two test setups were used for the full-scale panels, one setup for the 6.1 m (20 ft) tall panels, and another for the 12.8 m (42 ft) tall panels, as shown in Figure 9. For the 6.1 m (20 ft) panels, the test setup allowed for simultaneous application of gravity and lateral loads. Reverse-cyclic lateral loads

were applied to simulate the effects of wind pressure. The testing frame consisted of one braced frame on each side of the panel to support an upper cross beam which in turn provided the upper lateral support to the panel. The entire setup was anchored to the laboratory strong floor. A hydraulic actuator, supported by a strong reaction wall, was used to apply the lateral load. Each panel was simply supported in the testing frames at the top and bottom edge. The bottom of the panel was supported by a hinge, which restrained horizontal and vertical movements while allowing for rotation. The top of the panel was supported using a specially designed connection that restrained horizontal motion while allowing for vertical movement and rotation. Vertical loads were applied to the top of each corbel by

(a) 6.1 m (20 ft) Panels

b) 12.8 m (42 ft) Panels

Fig. 9: Full-Scale Panel Test setups

a hydraulic jack and cable. These vertical loads were provided to simulate the effects of a double-tee roof system. Lateral loads were applied by the actuator connected to a spreader beam system, which was used to push and pull the panel to simulate wind pressure and suction. Two loading tubes were provided at each quarter-height of each panel, one on each wythe, to distribute the lateral load across the width of the panel. The lateral loading mechanism included a vertical spreader beam that could shorten and elongate as the panel deformed to prevent the transfer of any unintended forces to the panel. The factored axial load was applied to the corbels before subjecting each panel to reverse-cyclic loading beginning at a level equivalent to 70% of the service load.

The test setup for the 12.8 m (42 ft) panels relied on testing the panels in an edgewise horizontal position as shown in Figure 9. While panels of this nature would usually be oriented vertically, the laboratory was not tall enough to test 12.8 m (42 ft) tall panels vertically. The test setup and instrumentation were designed to minimize any influence of the panel self-weight in the horizontal edgewise position. Each panel was

simply supported in the lateral direction on a 12.8 m (42 ft) span. Two matching hydraulic actuators were used to apply tension and compression loads in the lateral direction. The actuators were configured to produce matching loads at all times. Each actuator was attached to a panel using two square steel loading tubes, one on each surface of the panel. The loading tubes were bolted together though oversized holes in the panel to allow for application of lateral loads in either direction. The loading tubes were separated from the panel surface by thick neoprene pads on each wythe to avoid restraining the panel with the loading system. Equal lateral loads were applied to both quarter-spans by the hydraulic actuators.

In all six tests, panels were instrumented to measure lateral deflection, relative displacement between the two concrete wythes, surface strain of the concrete, and applied loads. The strain profile across the thickness of each panel was measured using four electrical-resistance strain gauges across the panel section at several locations along the height. In all six tests, each panel was subjected to nearly 4000 fully reversed lateral load cycles at levels of

at least 45% of the factored lateral wind load. The panels in the study were designed to resist the lateral wind pressures resulting from a design windspeed of at least 193 km/hr (120 mph).

The typical observed failure mode for the 6.1m (20 ft.) panels occurred at the top of the panel in the corbel zones. The failure mode was marked by separation at the top of the panel, visible as horizontal cracking on both faces. In all tests of 6.1 m (20 ft) panels, cracking was limited prior to failure and was concentrated above and below the load points, outside of the constant moment zone. Horizontal cracking at failure was concentrated on the outer panel face, as shown in Figure 10, likely due to the effect of the eccentric axial load keeping the inner panel face primarily in compression.

The behavior of the 12.8 m (42 ft) panels was primarily flexural. The typical cracking pattern observed on the inner wythe at the conclusion of testing is shown in Figure 11. In both 12.8 m (42 ft) tests, cracking on the outer wythe was similar to that on the inner wythe with primarily vertical cracks concentrated between the loading points.
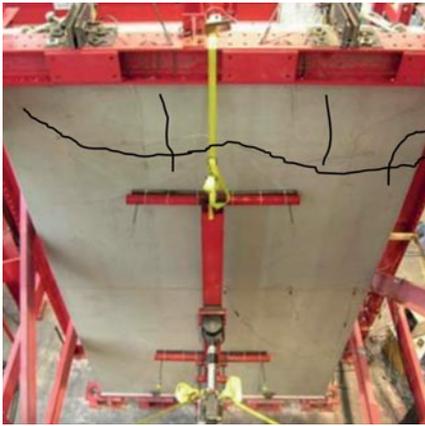
Fig. 10: Typical Failure of a Selected 6.1 m (20 ft) Panel

Fig. 11: Typical Failure Mode of a Selected 12.8 m (42 ft) Panel

Some localized cracking was observed at the panel ends.

Figure 12 depicts the measured mid-height lateral displacement response for a selected 6.1 m (20 ft) tall panel. Lateral deflection due to axial load alone is shown as the offset deflection at zero lateral load level. Panel behavior remained primarily linear to levels well beyond the factored lateral design load of through load level of 49 kN (11.1 kips).

For the 12.8 m (42 ft) panels, the lateral deflections at were measured at several points on the width of the panel to ensure that the edgewise orientation was not causing the panel to roll as it deformed. The measured lateral load-deflection response at midspan is shown in Figure 13 for a selected 12.8 m (42 ft) panel. Lateral deflection behavior remained linear to lateral load levels well beyond the service condition. Lateral load-deflection response became significantly nonlinear beyond the factored load level, indicating a ductile failure mode.

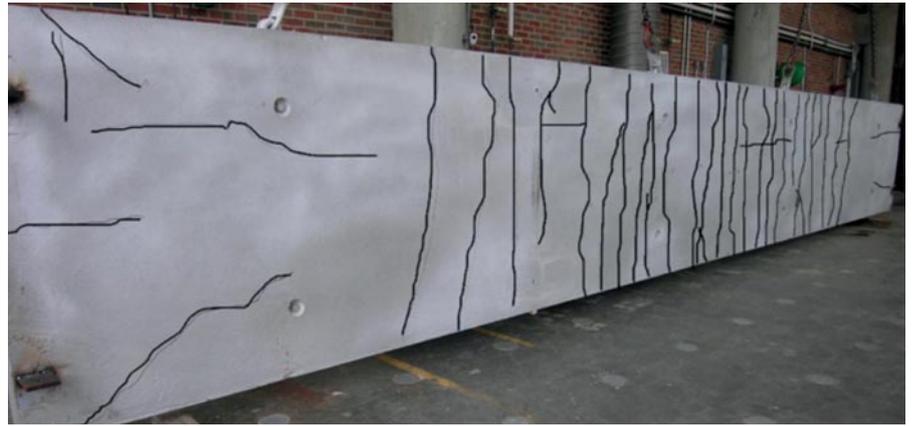One of the primary goals of the large-scale panel tests was to determine the degree of composite action developed for various panel configurations under varying degrees of applied axial and lateral load. Strain distributions through the panel cross-section were measured for each test. Results demonstrated that panels with sufficient CFRP grid connections developed levels of composite action at or near 100%, even at the factored load level, as shown in Figure 14. Lesser degrees of composite actions were seen in panels reinforced with lower levels of grid. The tests confirmed the ability of a designer to achieve a desired level of composite action by selecting appropriate CFRP grid connections.
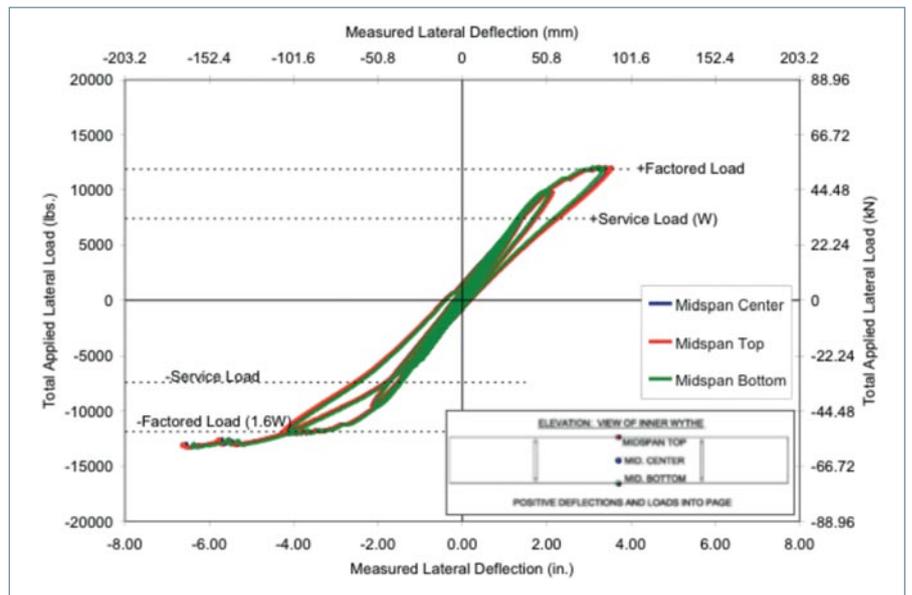

Fig.13: Applied Lateral Load vs. Measured Lateral Deflections at Midspan
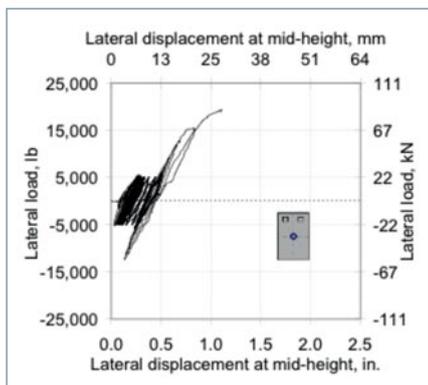

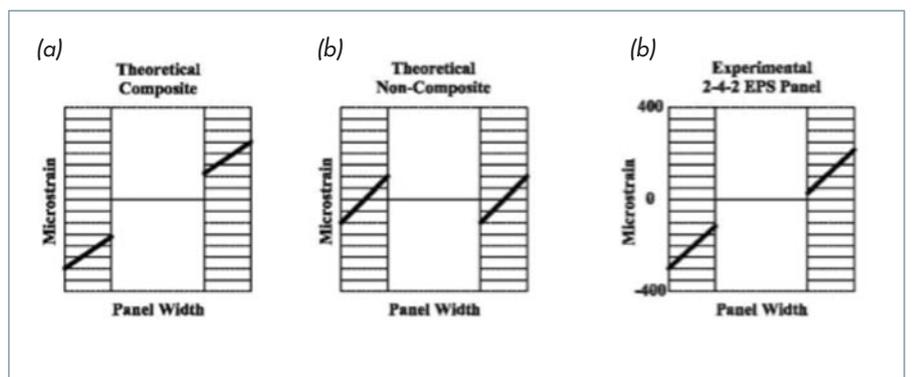Fig. 12: Load-Displacement Behavior of Tested 6.1 m (20 ft) Panels

Fig. 14: Strain Profiles; (a) Ideal Composite; (b) Ideal Non-composite; (c) Experimental

Fig. 15: Precast Composite Sandwich Panel in Uniform Pressure Chamber after Sustaining (Factored Load in Both Directions without Cracking)

Both the vertical and horizontal large-scale test series demonstrated the ability of precast concrete composite sandwich panels with CFRP grid wythe connections to safely withstand the factored design load in both directions. Even at load levels above the factored design load, data indicate that a significant level of composite action was developed between the two concrete wythes in both panels.

Tests of Sandwich Panel Wall System under Uniform Pressure

In addition to serving as loadbearing systems, precast concrete sandwich wall panels are also routinely used as cladding. In a cladding application, panels often serve as supports for window systems, and must provide lateral reactions for these window systems along the top and bottom edge of the precast panel. The wall system as a whole is subjected to lateral loads, often due to wind. The cladding panel must resist the uniform pressure applied to its own surface in addition to the pressure associated with the tributary area of any windows above or below. Complicating panel behavior is the fact that the lateral connections between the cladding panel and the supporting structure are not always placed symmetrically.

The special condition of a cladding panel wall system subjected to wind pressure was tested by assembling a full-scale wall system in a uniform pressure chamber. A precast concrete sandwich wall panel
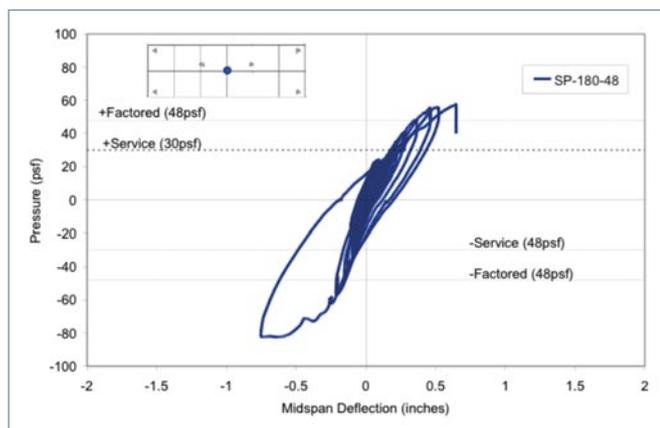

Fig. 16: Measured Load-Deflection Behavior for a Selected Architectural Panel

Fig. 17: Willow Creek Elementary School, Fleetwood, Pa..
Architect: AEM Architects, Inc. Precaster: High Concrete Group

Fig. 18: Cobb Performing Arts Centre, Atlanta, Ga..
Precaster: Metromont

using CFRP grid connections was attached to a supporting steel skeleton using field connections. A full-scale window system was installed above and below the precast concrete panel, however, for safety in the laboratory, fiberglass sheets were used instead of glass. The supporting steel skeleton was then closed in on all other sides so that the architectural wall panel system formed one face of a large sealed box. The wall panel system was then subjected to reverse cyclic lateral load cycles under pressure. For positive load cycles, the pressure in the box was increased, loading the wall panel and window systems uniformly.

For negative load cycles, the pressure in the box was decreased, likewise loading the wall system uniformly, but in the opposite direction. A photograph of the precast concrete architectural sandwich wall system in the test chamber is shown in Figure 15.

Tests were conducted to failure on two separate architectural panels. Prior to loading to failure, each panel wall system was cycled approximately 5000 times to loads in excess of the positive and negative service loads. After cyclic testing, the uniform lateral load on each panel wall system was increased to the factored level in the nega-

tive direction, then reversed to the factored load level in the positive direction. As shown in Figure 16, the panels behaved well through the factored load levels. Panel failure occurred at loads exceeding the factored level, and was caused by pull-out of connections embedded in the inner concrete wythe.

Finished Structures

The structures presented in Figures 17-20 are real-life examples of precat concrete insulated sandwich wall panels utilizing CFRP grid shear connections. ■

Fig. 19: Middlesex Center Warehouse, Jamesburg, N.J.. Architect: MH Architecture. Precaster: Oldcastle Precast Building Systems

Fig. 20: Tucker High School. Tucker, Ga..
Architect: Milton Pate Architects. Precaster: Metromont